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# Assessment of the recent land use change dynamics related to sugarcane expansion and the associated effects on water resources availability

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ABSTRACT

In this work, the Soil and Water Assessment Tool (SWAT) model was used to assess the impacts of the recent sugarcane expansion dynamics on the local water availability of two Brazilian basins (Fazenda Monte Alegre - FMA; Monte Mor - MM), which have experienced different land use change trends. To mitigate the issues concerning SWAT crop growth and water balance, it was performed for both basins a comprehensive model calibration and validation processes. Based on the results for water yields in FMA basin, it was possible to concluded that the sugarcane expansion over annual crops tends to increase stream flow during dry periods and decrease peak flows. In MM basin, the water yields suggest that urban areas expansion increases the stream flow in wet months, which can possibly harm flood vulnerability. In addition to these indications, the calibrated and validated SWAT model produced in this work can also be employed for the assessment of future scenarios with respect to not only land use changes, but also climate changes.



## 1. Introduction

Bioenergy production from different biomass sources has increased worldwide, making agricultural feedstocks for biofuels the main contributor for the general growth in agricultural demand in decades (Watkins Jr. et al., 2015). On the other hand, it is clear that large-scale production of biofuels will only be justified if their environmental and socioeconomic impacts are favourable, compared to other energy sources. As a consequence of the increase in bioenergy demand, sugarcane areas have expanded in Brazil, presenting different dynamics, in traditional and new cultivation areas, in diverse scales and replacing different land uses (Adami et al., 2012).

In 2013, according to Canasat data (Rudorff et al., 2010), Paraná hydrographic region comprised 95% of the sugarcane areas and was also responsible for 95% of the Brazilian Centre-South sugarcane expansion from 2006 to 2013. As land use changes can alter the partitioning of water at the land surface by affecting hydrological processes such as evapotranspiration (ET), infiltration, groundwater recharge, base flow, and runoff (Scanlon et al., 2005), the recent expansion of sugarcane has raised concerns about possible impacts on water availability (Scarpare et al., 2016a).

As the majority of sugarcane plantations in Brazil are rainfed, the parameter most frequently related to possible impacts on water resources availability due to sugarcane land use and expansion is the magnitude of the sugarcane evapotranspiration rate (Filoso et al., 2015). In fact, the estimations for sugarcane evapotranspiration during the development cycle in Brazilian states is about 30% higher than that for pasture, the primary crop that sugarcane has replaced (Hernandes et al., 2014). Similarly, sugarcane ET for the whole development cycle is about 70% higher than that for annual crops (Hernandes et al., 2014), which has been pointed out as a

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possible reason to harm the water budget when expansion occurs over annual crops (Guarenghi and Walter, 2016).

On the other hand, the duration of the development cycles in annual crops is about 3–4 months, while in sugarcane it takes about 12–18 months to complete the cycle. Considering that in Brazil 2 to 3 annual crop seasons can be produced in the same area (IBGE, 2016), the actual annual evapotranspiration differences between sugarcane and annual crops are certainly lower. Moreover, another study in an important agricultural frontier in Cerrado area (Spera et al., 2016) showed that displacing natural vegetation with annual crops may harm the precipitation regime, since the lower volume of water evapotranspired diminishes the amount of water recycled to the atmosphere, affecting the water regime. In this case, the double cropping practice was indicated in order to mitigate problems with low evapotranspiration volumes. Moreover, Loarie et al. (2011) suggested that temperature and evapotranspiration in sugarcane areas were closer to those of natural vegetation than to alternative crop/pasture mosaics. Consequently, provided that the native vegetation is maintained, water availability in regions with sugarcane croplands instead of annual crops or pasture lands may lead to a more regulated hydrologic cycle as sugarcane water balance components apparently are similar to those from forest.

Despite the indications and directions drawn in the recent studies, there was no consensus regarding the sugarcane expansion and impacts on water resources availability. This is possibly because, besides evapotranspiration, there are many factors in the water balance and hydrological processes that must be also considered, such as urbanization, precipitation regimes, other land use changes, local conditions, etc. (Stonestrom et al., 2009). Furthermore, the evapotranspired water eventually returns somewhere through rainfall and will contribute to the stream flow, either in the same basin or elsewhere (Lee et al., 2012). Therefore, an approach that combines the evaluation of hydrological processes and water balance components for different land use changes in sugarcane expansion process should lead to more conclusive answers to this question.

Hydrological models have been used to this purpose worldwide. One of the most employed models in watershed assessment is the Soil and Water Assessment Tool (SWAT), which is a time-continuous physically based model with spatially distributed parameters used to estimate stream flow, nutrient losses and sediment production in river basins (Arnold et al., 2012). The model has been applied in different scales and basins to predict impacts of management on water resources quality and availability (Neitsch et al., 2011), and its application is recommended by the United States Environmental Protection Agency (EPA) (Abbaspour et al., 2015). Similarly to other hydrological models, SWAT integrates different water balance components at the same time and space, enabling the assessment of the land use changes effects on evapotranspiration, crop yield, stream flow, precipitation, runoff, water yield, and others.

Bressiani et al. (2015) performed an extensive review of the SWAT application in Brazilian basins during the 1999–2015 period, compiling more than one hundred publications from Brazilian and international journals, conference proceedings, thesis and dissertations. The works explored stream flows and sediment loss for small and large basins in diverse Brazilian regions. Difficulties in SWAT input data gathering were pointed out in many of the assessed works, which is common as Brazil is a country with continental dimensions. Other problems in Brazilian SWAT simulations are possibly linked to inadequate representation of crops characteristics and inaccurate simulation of tropical perennial vegetation. On the other hand, the authors presented diverse data bases concerning SWAT main inputs, such as climate and hydrological data sources, digital elevation and soil maps and sources of land use information and maps.

Stimulated by the lack of scientific consensus about the effects of sugarcane expansion on the availability of water resources, this work performed an integrated evaluation of water availability at the watershed level in two basins within different regions in Brazil using SWAT as a modeling tool. The recent land use changes (LUC) were mapped for a watershed in a traditional sugarcane area, where the expansion is expected to be minor, and another in Southwest Goiás, where more intense sugarcane expansion has occurred. SWAT parametrization was made to mitigate the issues concerning crop characteristics and tropical perennial vegetation through a comprehensive calibration and validation process applied for both basins.

The land use change dynamics were then evaluated in association with the main components of the validated SWAT water balance (precipitation, water yield, and stream flow). Through these analyses, this work sought to provide insights and appropriate tools to help in the general assessment of the consequences of sugarcane expansion on the water resources availability at the basin level in Brazil.

## 2. Methods and data

The evaluation of impacts on water availability was based on the recent land use changes driven by sugarcane expansion in two Brazilian basins. LUC was assessed through ArcGIS supervised classification to obtain land use maps and land use change tables over the evaluated period. The assessment of the effects of land use change in the water availability was made using the Soil and Water Assessment Tool.

The input data required to use the SWAT model are basically divided into two groups: tabular data and spatial data. In the group of geographically referenced information are the digital terrain elevation model, the pedological map and the land use and cover map. The tabular data consisting of time series of precipitation, stream flow, minimum and maximum temperature, solar radiation, relative humidity and wind speed (Neitsch et al., 2011).

The model also requires some specific information, such as the number of layers and hydrological groups for each soil class within the basin, as well as information for each soil layer, such as available water capacity, saturated hydraulic conductivity, porosity, among other information. The model has a database with default information about the parameters for some types of land use/land cover. However, in specific cases, these parameters must be modified by the user (Neitsch et al., 2011).

The water balance components were obtained from a calibrated and validated SWAT model. After a sensitivity analysis, calibration and validation were made using statistical performance from the comparison between simulated and real values of stream flow from the two basins. The outputs of the calibrated and validated model such as the water yield, precipitation and stream flow, were evaluated in association to land use changes in each one of the two basins, in order to establish a relationship between the changes in land use/land cover and water availability (Fig. 1).

### 2.1. Study areas

This work evaluated two Brazilian basins, both located within the Paraná hydrographic region (Fig. 2). One basin hosts traditional sugarcane areas of the state of São Paulo, and the other is in new sugarcane areas towards the Cerrado[1] biome in the state of Goiás.

[1] *Cerrado* is the second largest Biome in South America, occupying about 22% of the Brazilian territory. Due to its biodiversity, Cerrado is recognized as the richest savannah in the world presenting innumerous species of plants and animals.

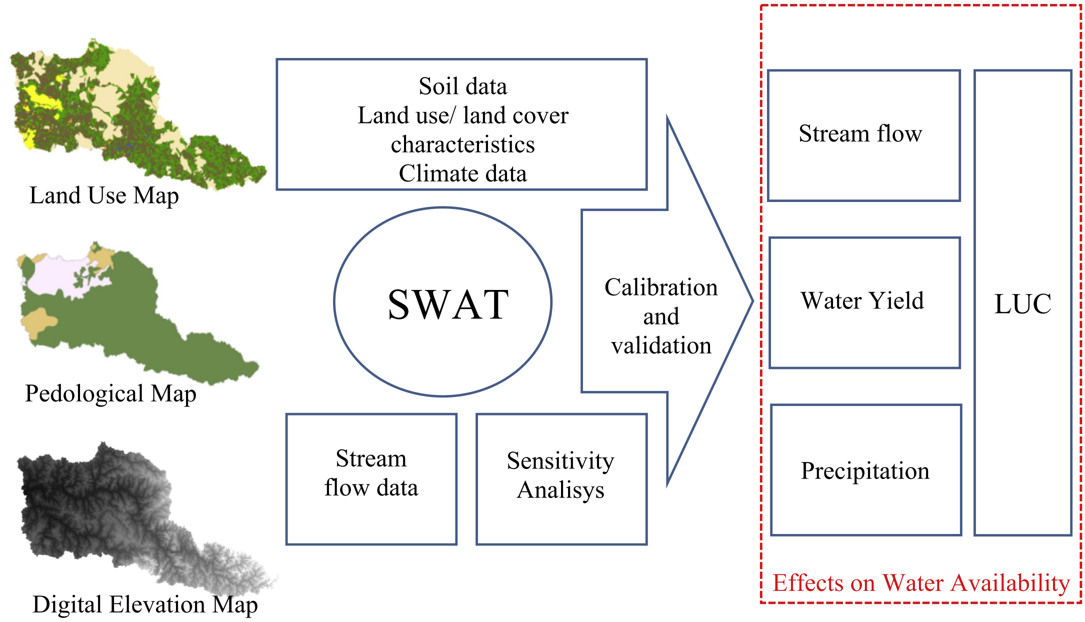


**Fig. 1.** Schematic representation of the methodological approach.

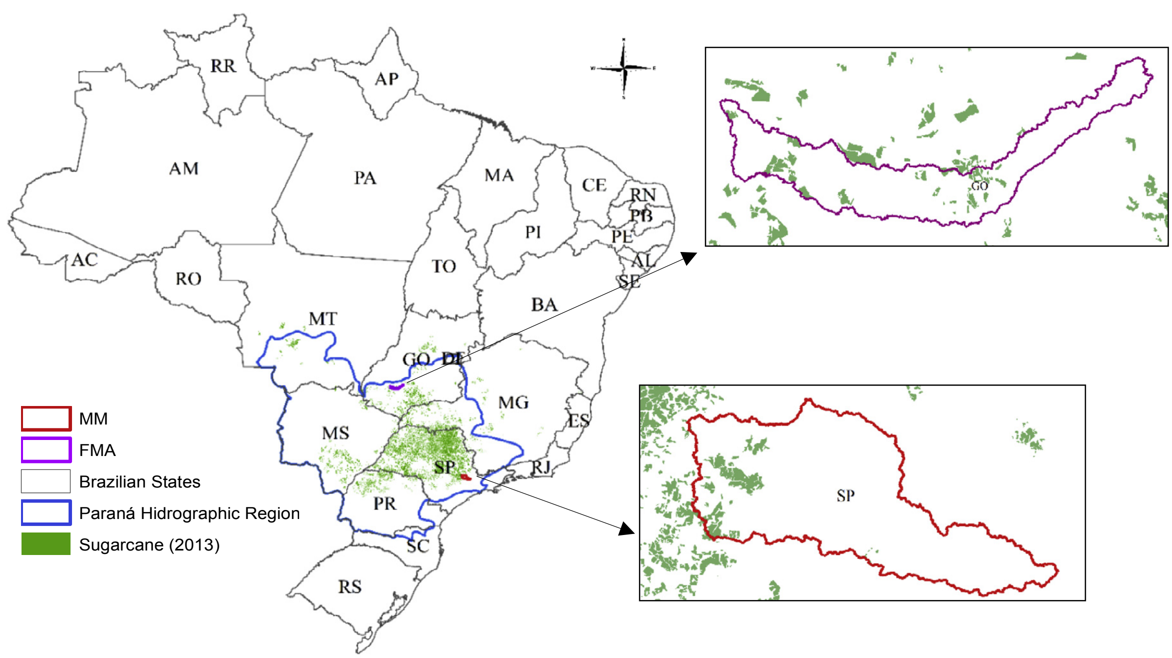


**Fig. 2.** Fazenda Monte Alegre and Monte Mor basins geographical position in Brazil.

The selection of the study areas was guided by the data availability (stream flow and climate data), the variability of edaphoclimatic conditions, the sugarcane crop occurrence and the similarity between the basin drainage areas.

Monte Mor basin (MM) is located in the state of São Paulo. It presents a Subtropical climate, with high temperatures and wet period in the summer, and a moderate and dry winter. The drainage area hosts a traditional sugarcane zone belonging to Campinas and Jundiaí micro regions and with urban features, partially covering twelve municipalities. The sugarcane areas in this basin present a stagnation trend due to, among other socioeconomic aspects, legal issues in pre-harvest burning and due to topography constraints for mechanical harvesting. Unpublished results derived from local interviews indicate a replacement of sugarcane areas with slopes above 15% by private residential areas. Supervised classification for Monte Mor basin's satellite images from the recent past years corroborated both the sugarcane areas stagnation and the urban areas expansion.

On the other hand, the Fazenda Monte Alegre basin (FMA) in southwest Goiás presents a strong sugarcane expansion tendency (Scarpare et al., 2016). This basin has no urban areas, being totally covered by Cerrado (ANA, 2015), pasture and annual croplands. It is located in a Tropical climate with dry winter and rainy and hot summer seasons, and all its drainage area remains within the rural

area of Rio Verde municipality.

### 2.2. SWAT modeling

SWAT computes water, sediment and nutrient balance combining homogeneous land use, topography, management and soil characteristics into hydrologic response units (HRU). The HRU results for the hydrological processes involved in simulations (canopy interception of precipitation, partitioning of precipitation, irrigation water between surface runoff and infiltration, redistribution of water within the soil profile, evapotranspiration, lateral subsurface flow from the soil profile, and return flow from shallow aquifers) are integrated in sub-basins and then combined to generate a weighted basin response. The basin water balance in SWAT is composed mainly by the precipitation (PREC) that falls within the basin drainage area, the actual evapotranspiration (ET) for the basin and the water yield (WY), which comprises the surface, subsurface and lateral runoff (Gassman et al., 2007). Subbasins and drainage channels can be created from the digital terrain elevation model (DEM). The runoff is calculated for each HRU, which are unique combinations of land use and cover, soil type and slope, thus promoting a better description of the water balance in the basin (Eq. (1)). The total stream flow is given by Equation (2) (Neitsch et al., 2011).

$$SW_t = SW + \sum_{i=1}^{t} (P_i - q_i - ET_i - q_{lat.i} - q_{ret.i}) \quad (1)$$

$$Q = q_i + q_{lat.i} + q_{ret.i} - Tloss_i - pa \quad (2)$$

Where *SWt* is the final amount of water in the soil (mm); *SW* is the initial amount of water in the soil (mm); *t* is the time (days); Pi is the precipitation (mm) on day *i*; *qi* is the surface runoff (mm) on day *i*; *ETi* is the evapotranspiration (mm) on day *i*; *qlat.i* is the lateral flow (mm) on day i; *qret.i* is the return flow (mm) on day *i*; *Q* is the total flow; *Tlossi* is the rate of water lost to the water table on day *i*; and *pa* is the water accumulated in small depressions of the terrain.

In this work, potential evapotranspiration was estimated by Penman-Monteith approach, and evaporation from plant and soil are calculated independently (Ritchie, 1972). Surface runoff is estimated with a modification of the Soil Conservation Service (SCS) curve number method from the United States Department of Agriculture (USDA SCS, 1972). The crop growth and the management practices are based on the Environmental Policy Integrated Climate (EPIC) crop growth model (Arnold and Allen, 1996).

More details about model equations and processes can be found in the SWAT Theoretical Documentation in Neitsch et al. (2011).

### 2.3. Watershed delineation

Digital Elevation Maps (DEM) were used to define the basins drainage areas, outlets, subbasins and drainage channels (Fig. 3). Maps were obtained from ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) onboard the NASA satellite “Terra”.

Drainage areas of the selected watersheds were defined through the SWAT automatic watershed delineation module, using the geographic coordinates of the outlets from the Brazilian Water Agency (ANA) flow monitoring points 60.778.000 (FMA) and 62.420.000 (MM) (ANA, 2014). In both basins, the real drainage areas given by ANA and the drainage areas done by SWAT watershed delineation module were very similar (Table 1).

### 2.4. Land use maps and Land Use Update

The SWAT module “Land Use Update” (LUP) enables the land use change control throughout the simulation years using only land use change in percentages (Pai and Saraswat, 2011). Thus, according to the available stream flow data period, it was defined a base map for FMA and MM basins and other four support maps were made in order to update land use changes in the basins. Support maps were intersected with the base map creating the percentages of changes.

Base maps (Fig. 4) and the other required land use maps were prepared using ArcGIS 10.1 supervised classification on LandSat images (Table 2). For MM basin, base map corresponds to the land use in 1996, while for FMA, basin base map refers to the land use in 2004.

The automated classification was confirmed by comparison to the Google Earth images, when it was available at the correspondent site and date, and also by association to the MODIS sensor 1 time-series (Freitas et al., 2011). As sugarcane was the crop of interest, classification was made manually, with the support of CANASAT project maps (Rudorff et al., 2010). Urban areas were also manually classified.

Land uses were defined using SWAT crop database as described in Table 3, based on satellite images classification and in agricultural information from the Brazilian Geography and Statistics Institute (IBGE, 2016).

### 2.5. Climate and soil data

Required climatic inputs were precipitation, maximum and minimum temperature, solar radiation, relative humidity, and wind speed, all in daily time-step. Except for precipitation, climatic data were obtained from the National Centers for Environmental Prediction - Climate Forecast System Reanalysis (Saha et al., 2014), which provides more than 30 years of weather data for the whole world in a 38-km grid.

Precipitation data was collected from all the available ANA rain gauge stations in FMA and MM basin areas. The rain gauge stations that have influence in precipitation occurrence in both basins were determined by the Thiessen polygons method and then added to the model database (Table 4). In FMA basin, data gaps represented in average 7% of the total precipitation records, while 6% of the records were missing in MM basin rain gauge stations. In both basins, all gaps in precipitation data were filled by the SWAT weather generator WGEN (Arnold et al., 2012).

Soil maps for MM basin was provided by the Agronomic Institute of Campinas (IAC), in 1:500,000 scale (Oliveira et al., 1999). For the FMA basin, the soil map was found in Goiás State Geosystem Information (SIEG), in 1:250,000 scale (SIEG, 2014).

Considering the Brazilian Soil Classification System (SiBCS) (EMBRAPA, 2013), MM basin soil map shows a large area of 'Argissolos' with spots of 'Latossolos Vermelhos' and 'Latossolos Vermelho-Amarelos'. FMA basin is surrounded by ‘Cambissolos’, with ‘Latossolos’ in the middle. In World Reference Base (IUSS Working Group WRB, 2014), “Argissolos” correspond to Lixisols, “Latossolos” are classified as Ferralsols and “Cambissolos” are Cambisols (Rizzo et al., 2016).

The physicochemical soil parameters for MM soils were from a public database from the Brazilian Agricultural Research Corporation (EMBRAPA) (EMBRAPA, 2014), allowing to fill parameters such as the number of layers, hydrological groups, maximum rooting depth, moist bulk density, organic carbon content and soil texture. For FMA basin, the same soil parameters were inserted in the soil database, with specific data for the Brazilian Cerrado area, from Lima et al. (2014). The available water capacity and the saturated hydraulic conductivity for both basins were calculated through

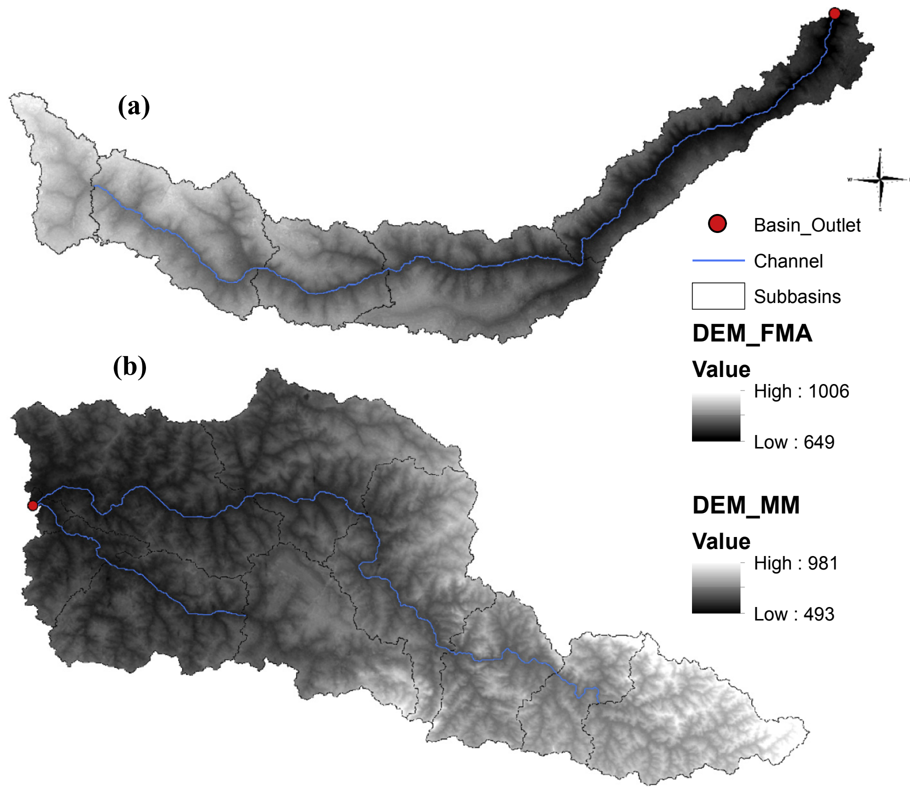


**Fig. 3.** Digital elevation maps, subbasins, outlets and drainage channels for Fazenda Monte Alegre (a) and Monte Mor (b) Brazilian basins. Digital elevation legend in meters.

**Table 1**
Fazenda Monte Alegre and Monte Mor watershed characterization.

| Parameters | Fazenda Monte Alegre | Monte Mor |
|---|---|---|
| Drainage Area ANA ($km^2$)[a] | 808 | 697 |
| Drainage Area SWAT ($km^2$)[a] | 805 | 698 |
| Basin Outlet Latitude (DD) | −17.33 | −22.96 |
| Basin Outlet Longitude (DD) | −50.77 | −47.30 |
| Climate (Köeppen) | Tropical Savannah (Aw) | Humid Subtropical (Cwa) |
| Annual Rainfall (mm) | 1550 | 1300 |
| Mean Annual Temperature (°C) | 23 | 22 |

[a] Less than 0.5% of difference between basins drainage areas given by ANA and delineated using SWAT.

pedotransfer functions adapted to tropical soils (Barros et al., 2013).

### 2.6. SWAT setup, calibration and validation

The assurance of reliable Leaf Area Index (LAI) values and behavior were essential for this work as they directly influence crop evapotranspiration and water balance (Strauch and Volk, 2013). Thus, in order to minimize inconsistencies, management and crop files were modified to better represent FMA and MM conditions (see Fig. 5). The modifications were made to all crop and management parameters that were available in the literature (Tables 5 and 6).

For orchard areas, it was considered the orange parameters since the citrus production is very common in the municipalities covered by the MM basin (IBGE, 2016). In management operations, annual crop areas were set as a soybean-corn rotation. Concerning sugarcane, a six-year cycle was considered, with a plant cane (one year and a half of development) followed by four sugarcane ratoons. For the remaining perennial cultures (Forest, Cerrado, Orchard and Pasture), the problem with the dormancy period was mitigated through the “Harvest only” and the “Begin of growing season” operations scheduled to happen in the winter season.

Before calibration, tests were made in order to define the more appropriate method for the Curve Number (CN) estimation regarding stream flow results. For MM basin, best outcomes were obtained by the Evapotranspiration Method. For FMA basin, on the other hand, the USDA Method fitted better. For model calibration, validation, sensitivity and uncertainty analysis it was used the SUFI2 algorithm in SWAT-CUP, which is a program interface for SWAT used to perform a combined calibration-uncertainty analysis (Abbaspour et al., 2015). Calibration and validation were performed in monthly time step, with two years of model warm up. Simulation periods were defined based on the stream flow data availability in FMA and MM basins outlets. For FMA basin, simulation started in 2001 and finished in 2012. For MM basin the simulation period was from 1995 to 2007.

All SWAT parameters directly involved in stream flow process were considered in the calibration on SWAT-CUP (Table 8) (Barbarotto Jr, 2014). Parameter changes in calibration were made using the relative method for CN2, SOL_AWC, SOL_K, SOL_ALB, SLSUBBSN and CANMX, within the parameter ranges, in order to preserve the differences related to the land use, the slope and the

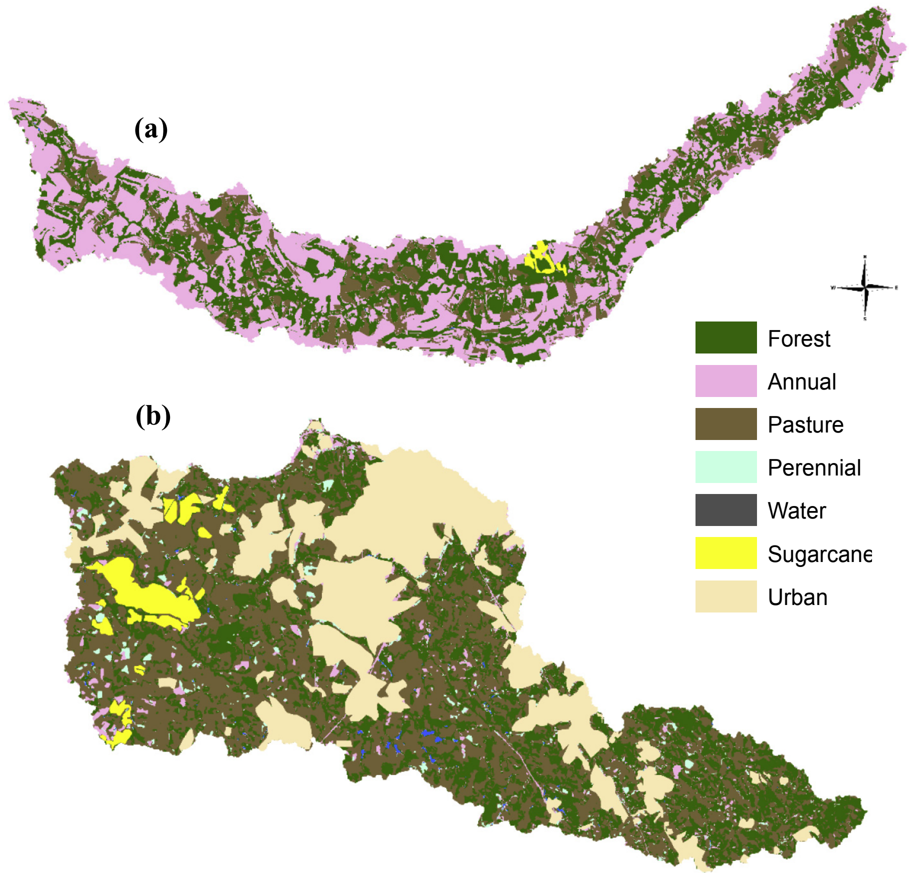


**Fig. 4.** Land use base maps classified as sugarcane, forest, annual crops, pasture, perennial crops, water and urban areas for FMA (a) and MM (b) Brazilian basins.

**Table 2**
LandSat image dates for the construction of base maps and support land use update maps.

| Basin | Year | Month | Day |
|---|---|---|---|
| Monte Mor | 1996 | March | 26 |
| | 1999 | March | 19 |
| | 2001 | April | 25 |
| | 2004 | February | 29 |
| | 2007 | March | 25 |
| Fazenda Monte Alegre | 2004 | June | 16 |
| | 2005 | April | 16 |
| | 2008 | April | 24 |
| | 2010 | April | 14 |
| | 2011 | April | 17 |

**Table 3**
Land use and land cover maps for SWAT correspondence in FMA and MM basins.

| Land Use | FMA (SWAT Code) | MM (SWAT Code) |
|---|---|---|
| Sugarcane | Sugarcane (SUGC) | |
| Water | Water (WATR) | |
| Pasture | Pasture (PAST) | |
| Annual Crops | Soybean/Corn Rotation (SOYB-CORN) | |
| Cerrado/Forest | Range Brush (RNGB) | Forest Evergreen (FRSE) |
| Perennial Crops | ———————— | Orchard (ORCD) |
| Urban Areas | ———————— | Residential-Medium Density (URMD) |

soil characteristics. For the remaining parameters, values included in the ranges were replaced during the calibration process. Calibration was performed in two iterations: the first one with larger parameter ranges as presented in Table 8, and the second one with narrower intervals, given by the calibration process in the first iteration.

Model performance was statistically evaluated using the Correlation Coefficient (R2), the Percent Bias (PBIAS), the RMSE-observations standard deviation ratio (RSR), the bR2 coefficient (bR2) (Bressiani et al., 2015) and the Nash-Sutcliffe Efficiency (NSE) (Table 9) (Moriasi et al., 2007). Uncertainty analysis in SUFI2 calibration process was quantified through the P-factor and the R-factor indexes. The P-factor is the percent of observations that are within the given uncertainty bounds and R-factor is the average width of the given uncertainty bounds divided by the standard deviation of the observations. Ideally, a perfect simulation is achieved when P-factor is equal to 1 and R-factor is equal to zero. However, in real situations the aim is to obtain a P-factor around 1 and a R-factor as close as possible to zero. For stream flow, the combination of a P-Factor larger than 0.7 with a R-Factor below 1 indicates a strong calibration process (Abbaspour et al., 2015).

## 3. Results and discussion

### 3.1. SWAT calibration and validation

FMA and MM basins have both a wet and warm period from September/October to March/April, and a dry and moderate temperatures period from April/May to August/September. Thus, leaf area index (LAI) is expected to achieve, at least in perennial and semi-perennial crops, greater values in wet months and lower values in dry or harvest periods. As can be seen in Fig. 4, these

**Table 4**
ANA rain gauge stations used in SWAT simulation for FMA and MM basins.

| Rain Gauge | | Code | Latitude (DD) (Decimal Degrees) | Longitude (DD) | Altitude (m) |
|---|---|---|---|---|---|
| FMA | Ponte Rio Doce | 1751001 | −17.86 | −51.4 | 755 |
| | Fazenda Paraíso | 1750008 | −17.47 | −50.77 | 680 |
| | Montividiu | 1751004 | −17.33 | −51.26 | 797 |
| | Ponte Rodagem | 1750004 | −17.33 | −50.68 | 709 |
| MM | Itatiba | 2246038 | −22.94 | −46.83 | 690 |
| | Monte Mor | 2247058 | −22.96 | −47.3 | 560 |
| | Indaiatuba | 2347007 | −23.08 | −47.22 | 630 |

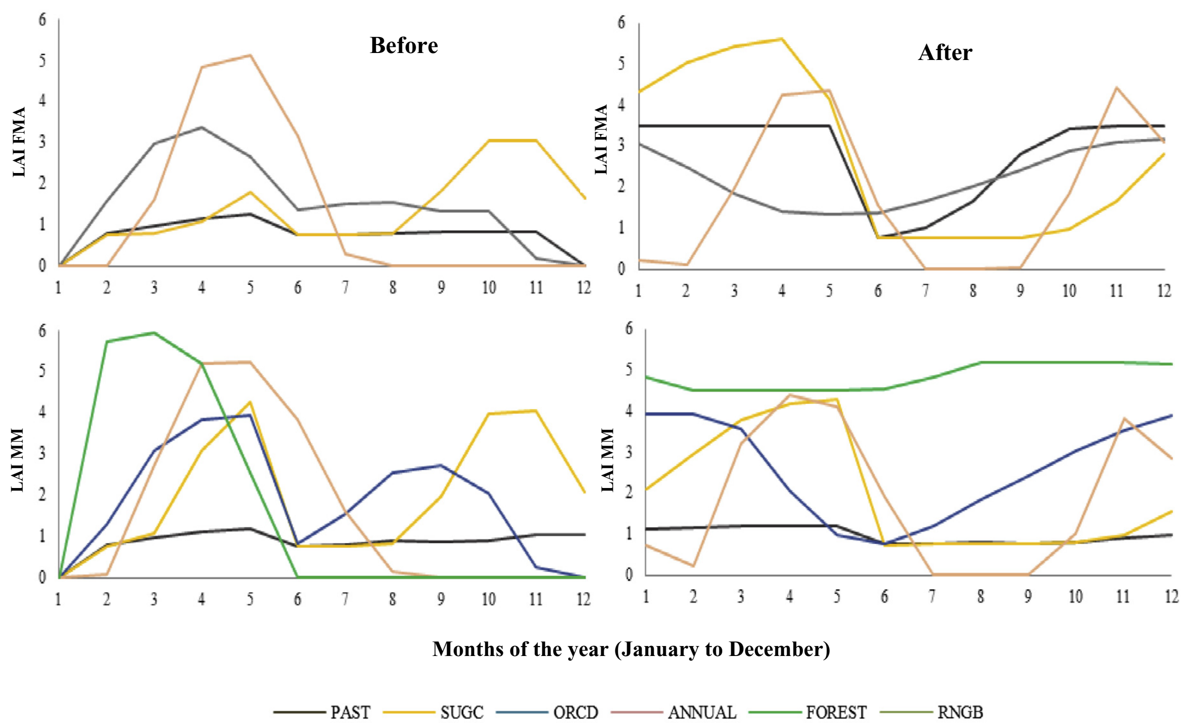


**Fig. 5.** Leaf Area Index (LAI) behavior during the year, before and after the adjustments in crop parameters and management files for the Fazenda Monte Alegre (FMA) and Monte Mor (MM) basins.

trends are observed after the model adjustments, providing more reliable LAI values and behavior for FMA and MM basins. Soybean and corn rotation were also very well represented, with plant and harvest dates well marked and reasonable LAI peaks, as well as in sugarcane crop (semi-perennial crop).

In order to evaluate the crop evapotranspiration and crop yields results, it was made a comparison between SWAT results and literature/soft data (Table 7). Results from SWAT corresponds to the average values between the two assessed basins over the whole simulated period.

All crop evapotranspiration amounts from SWAT were within the range from literature. Except for corn, evapotranspiration values were closer to the lower limits, which is reasonable since the crops were rainfed (no irrigation was considered). Crop yields were also very similar to those found in the literature, with the orange productivity as the most discrepant value. In this case, and also for pasture, values were below the references possibly because some management considerations since the considered crops were not fertilized in the simulations (see Table 5).

Acceptable results for crop evapotranspiration and yield, even with no specific calibration, reinforces the importance of the model setup step in achieving reliable representation of the water balance components and crop related outputs. Regarding the significance of the evapotranspiration in water balance results, although laborious and time consuming, it is imperative to be sure of using the best crop and management related parameters always as possible in order to get consistent simulations.

A sensitivity analysis was made using the parameter ranges defined in the SWAT database, which correspond to the absolute maximum and minimum values that the parameters can reach. So, the sensitivity results associated to the parameter's character helped to define the calibration ranges. In both basins, the most sensitive parameter was the CN2. Soil parameters, ESCO, CANMX, ALPHA_BF and SLSUBBSN also presented high influence in FMA and MM basins.

Calibrated values for the parameter can be found in Table 8. The hydrographs with observed and calibrated/validated (simulated) stream flow values for both basins are presented in Fig. 6. In FMA and MM basins, the model adjustment was good in the considered period. Despite some discrepancies in peak stream flow values, it was observed a better fit in the calibration period in both hydrographs. In general, stream flow simulated in SWAT model were more similar to the observed values in the dry months. This behavior favors the analysis of water availability since the reference flow for water grants concession are derived from the stream flow values in dry periods.

**Table 5**
Management operations for all considered land uses in FMA and MM basins.

| Land Use | Year | Date | Operation | Quantity (kg $ha^{-1}$) |
|---|---|---|---|---|
| Soybean and corn rotation[b] | 1 | 5-Feb | Soybean Harvest and kill | |
| | 1 | 6-Feb | Corn Nitrogen application | 40 |
| | 1 | 6-Feb | Corn Phosphorus application | 20 |
| | 1 | 10-Feb | Corn Plant | |
| | 1 | 1-Jul | Corn Harvest and kill | |
| | 1 | 25-Sep | Soybean Nitrogen application | 7 |
| | 1 | 25-Sep | Soybean Phosphorus application | 33 |
| | 1 | 1-Oct | Soybean Plant | |
| | 1 | 28-Feb | Sugarcane Plant | |
| Sugarcane | 1, 2, 3, 4, 5 | 28-Feb[c];1-Aug[d] | Nitrogen application[a] | 100 |
| | 1, 2, 3, 4, 5 | 28-Feb[c];1-Aug[d] | Phosphorus application[a] | 30 |
| | 2, 3, 4, 5 | 01-Aug | Begin of growing season | |
| | 2, 3, 4, 5, 6 | 31-Jul | Harvest only | |
| | 6 | 01-Sep | Kill Sugarcane | |
| Forest and Pasture | 1 | 30-Jun | Harvest only | |
| | 1 | 15-Jul | Begin of growing season | |
| Orchard | 1 | 1-Jun | Harvest only | |
| | 1 | 1-Jul | Begin of growing season | |
| Cerrado | 1 | 31-Aug | Harvest only | |
| | 1 | 1-Sep | Begin of growing season | |

[a] Rosseto and Dias, 2005.
[b] Strauch et al., 2013.
[c] Plant Cane.
[d] Sugarcane Ratoon.

**Table 6**
Adjusted crop related parameters for all considered land uses in FMA and MM basins.

| Parameter | SWAT folder | Description | SUGC | RNGB | PAST | SOYB | CORN | FRSE |
|---|---|---|---|---|---|---|---|---|
| ALAI_MIN | crop.dat | Minimum leaf area index for plant ($m^2$ $m^{-2}$) | – | 1.35[b] | 0.75[g] | – | – | 4.5[a] |
| BIO_E | crop.dat | Radiation Use Efficiency ((kg $ha^{-1}$)/(MJ $m^2$)) | 36[c] | 20[b] | – | – | – | 20[b] |
| BLAI | crop.dat | Maximum potential leaf area index ($m^2$ $m^{-2}$) | 6[d,e] | 3.5[b] | 3[a,g] | 5[i,j] | 6[m] | 6[a,p] |
| DLAI | crop.dat | Fraction of PHU when LAI begins to decline | – | 0.53[b] | – | – | – | – |
| FRGRW1 | crop.dat | Fraction of PHU corresponding to the 1st point on the optimal leaf area development curve | – | 0.07[b] | – | – | – | – |
| FRGRW2 | crop.dat | Fraction of PHU corresponding to the 2nd point on the optimal leaf area development curve | – | 0.5[b] | – | – | – | – |
| GSI | crop.dat | Maximum stomatal conductance at high solar radiation and low vapor pressure deficit (m $s^{-1}$) | 0.0025[a] | 0.003[b] | 0.003[a] | – | – | 0.005[a] |
| LAIMX1 | crop.dat | Fraction of BLAI corresponding to the 1st point on the optimal leaf area development curve | – | 0.15[b] | – | – | – | – |
| LAIMX2 | crop.dat | Fraction of BLAI corresponding to the 1st point on the optimal leaf area development curve | – | 0.95[b] | – | – | – | – |
| TBASE | crop.dat | Minimum temperature for plant growth (∘C) | 16[f] | 10[b] | – | 10[i,j] | 10[m,n] | – |
| VPDFR | crop.dat | Vapor pressure deficit (kPa) corresponding to the second point on the stomatal conductance curve | – | 1.6[b] | – | – | – | – |
| CHTMX | crop.dat | Max canopy height (m) | 4[a] | 10[a] | – | – | – | 30[a] |
| RDMX | crop.dat | Max root depth (m) | 2[a] | 6[a] | 1.5[a] | – | – | 6[a] |
| CANMX | .hru | Maximum canopy storage (mm) | 1[a] | 1.6[a] | 0.7[a] | 0.7[l] | 1[o] | 1.8[a] |
| ESCO[s] | .hru | Evaporation compensation factor | 0.95 | 0.93 | 0.90 | 0.90 | 0.90 | 0.93 |
| PHU_PLT | .mgt | Total number of heat units or growing degree days needed to bring plant to maturity | 5700[f,q]/ 4500[f,r] | 4500[b] | 4500[h] | 1800[j] | – | 4500[h] |
| T_OPT | crop.dat | Optimum temperature for plant growth (∘C) | 25[f] | – | – | 30[i] | 30[m] | – |

[a] Da Silva, 2013.
[b] Strauch and Volk, 2013.
[c] Ferreira Junior, 2013.
[d] Cabral et al., 2012.
[e] Scarpari and Beauclair, 2008.
[f] Scarpare, 2011.
[g] Zanchi et al., 2009.
[h] Considering the PHU accumulated in one year, as for sugarcane ratoon.
[i] Oliveira et al., 2011.
[j] Martorano, 2007.
[l] Considering the same value as in pasture.
[m] Gaiewski., 2009.
[n] Assis et al., 2006.
[o] Considering the same values as in sugarcane.
[p] Carreire, 2009.
[q] Plant Cane.
[r] Sugarcane Ratoon.
[s] ESCO values were based on the literature values variation from Da Silva (2013) and Strauch and Volk (2013). However, after personal communication with SWAT model makers, they suggested a maximum value of 0.95. Thus, ESCO values were adapted considering the maximum of 0.95.

**Table 7**
Values of crop evapotranspiration and crop yields from SWAT and from literature.

| | SWAT ET (mm) | Ref ET (mm) | SWAT Yield (Mg $ha^{-1}$) | Ref Yield (Mg $ha^{-1}$) |
|---|---|---|---|---|
| Sugarcane | 895.5 | 800–2000[a] | 81 | 78[f] |
| Soybean | 503 | 450–800[b] | 4 | 3[f] |
| Corn | 424.5 | 350–500[c] | 5.5 | 4.4[f] |
| Orange | 1100 | 1000–1400[d] | 12 | 20[f] |
| Pasture | 942.5 | 800–1600[e] | 9 | 10–20[g] |

[a] Santos, 2005.
[b] Farias et al., 2007.
[c] EMBRAPA, 2016.
[d] Santos Filho, 2005.
[e] Voltolini et al., 2011.
[f] CONAB, 2016 (Average yield for the recent 10 years).
[g] Costa, 2004.

**Table 8**
Calibrated parameters for FMA and MM basins.

| Parameter | Description | Units | Range | FMA Values | MM Values |
|---|---|---|---|---|---|
| GWQMN | Threshold depth of water in the shallow aquifer required for return flow to occur | mm | 0–5000 | 141.32 | 2489.84 |
| CN2 | SCS runoff curve number for moisture condition 2 | – | −0.2–0.2 | 0.84 | 0.82 |
| GW_REVAP | Groundwater "revap" coefficient | – | −0.02–0.2 | 0.02 | 0.08 |
| SOL_K | Saturated hydraulic conductivity | mm $h^{-1}$ | −0.2–1 | 1.97 | 1.94 |
| SLSUBBSN | Average slope length | m | −0.2–1 | 0.96 | 1.01 |
| ALPHA_BF | Baseflow alpha factor | $day^{-1}$ | 0–1 | 0.11 | 0.03 |
| EPCO | Plant uptake compensation factor | – | 0–1 | 0.91 | 0.48 |
| SOL_AWC | Available water capacity of the soil layer | mm $mm^{-1}$ | −0.2–1 | 0.89 | 1.45 |
| GW_DELAY | Groundwater delay | day | 0–500 | 452.1 | 206.38 |
| SURLAG | Surface runoff lag time | day | 0–10 | 4.01 | 4.33 |
| ESCO | Soil evaporation compensation factor | – | −0.2–0 | 0.81 | 0.82 |
| CH_K2 | Effective hydraulic conductivity in main channel alluvium | mm $h^{-1}$ | 0–150 | 31.1 | 16.18 |
| SOL_ALB | Moist soil albedo | – | −0.2–1 | 1.78 | 0.97 |
| REVAPMN | Threshold depth of water in the shallow aquifer for "revap" to occur | mm | 0–500 | 497.62 | 435.34 |
| CANMX | Maximum canopy storage | mm | −0.5–0.5 | 0.77 | 0.62 |
| CH_N2 | Manning's "n" value for the main channel | – | 0–1 | 0.7 | 0.11 |

**Table 9**
Model calibration and validation performance for FMA and MM basins.

| Statistical Parameters | | Calibration | | Validation | | Calibration + Validation | |
|---|---|---|---|---|---|---|---|
| FMA | $R^2$ | 0.84 | Satisfactory | 0.8 | Satisfactory | 0.83 | Satisfactory |
| | $bR^2$ | 0.74 | Satisfactory | 0.76 | Satisfactory | 0.74 | Satisfactory |
| | NS | 0.84 | Very Good | 0.77 | Very Good | 0.82 | Very Good |
| | RSR | 0.41 | Very Good | 0.48 | Very Good | 0.43 | Very Good |
| | PBIAS | −0.13 | Very Good | −3.37 | Very Good | −1.32 | Very Good |
| MM | $R^2$ | 0.85 | Satisfactory | 0.69 | Satisfactory | 0.75 | Satisfactory |
| | $bR^2$ | 0.71 | Satisfactory | 0.61 | Satisfactory | 0.64 | Satisfactory |
| | NS | 0.85 | Very Good | 0.64 | Satisfactory | 0.74 | Good |
| | RSR | 0.39 | Very Good | 0.6 | Good | 0.51 | Good |
| | PBIAS | −1.82 | Very Good | 5.26 | Very Good | 1.62 | Very Good |

According to Moriasi et al. (2007) and Gassman et al. (2007) criteria, stream flow calibration and validation performance were statistically satisfactory (Table 9) for the two assessed locations. Considering the second iteration of the calibration process, in accordance to Abbaspour et al. (2007) and Abbaspour et al. (2015), uncertainty analysis also gave proper values for R-factor (0.60 for FMA and 0.86 for MM) and P-factor (0.85 for FMA and 0.86 for MM). Hence, the satisfactory statistical response combined to the appropriate uncertainty results indicates a consistent calibration process, enabling a reliable use of SWAT water balance components.

Values in Table 8 showed that soil related parameters such as SOL_K, SOL_AWC and SOL_ALB presented the most significant changes in the calibration process. These results were somehow expected as the soil information and data are relatively scarce in Brazil, which made SOL_K and SOL_AWC to be obtained from pedotransfer functions. Thus, the uncertainty and error related to these parameters were high than for the others.

### 3.2. Land use change and water resources

Land use changes for the considered period were obtained by the comparison between the most recent land use map and the base map (Fig. 7). In MM basin, from 1997 to 2007, forests (native and/or planted) and urban areas showed an increase of 2500 ha, each class. Sugarcane areas were stable, with a slight increase of 300 ha. Pasture lands were reduced in 3400 ha, followed by the decreases in annual (1500 ha) and perennial crops (1000 ha).

In contrast, in FMA basin annual crops had a large expansion from 2003 to 2011, reaching an increase of almost 13,000 ha. Sugarcane also increased more than 3000 ha. Forest and pasture lands presented a reduction of 7000 and 8600 ha, respectively. In general, land use changes in FMA basin were more intense than changes in MM basin, considering absolute numbers.

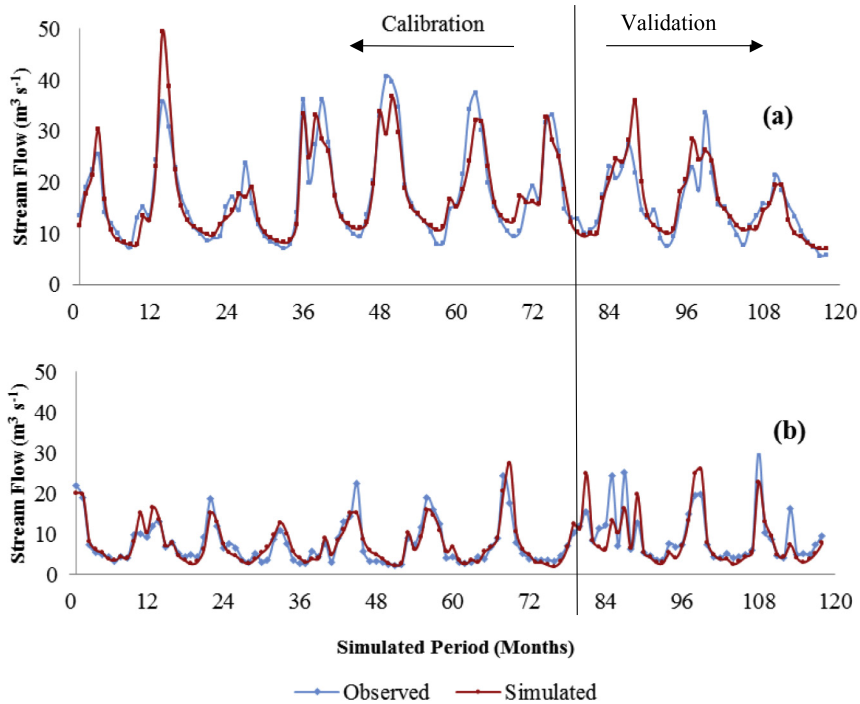


Fig. 6. Observed and simulated stream flow values for FMA (a) and MM (b) Brazilian basins.

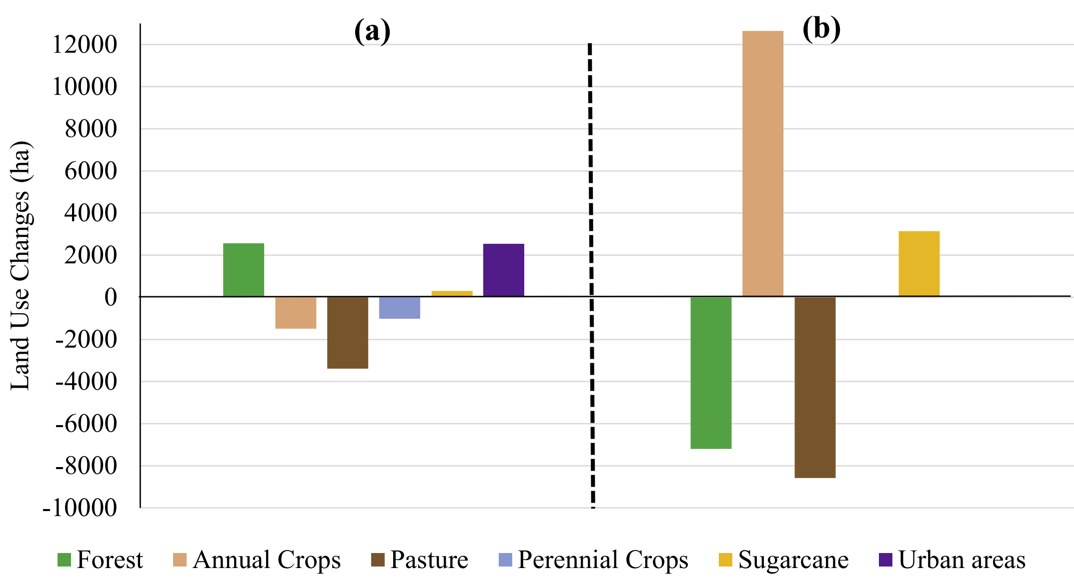


Fig. 7. Total land use changes in MM (a) and FMA (a) Brazilian basins.

Besides the total land use changes, it was possible to point over which land use classes expansions and reductions have occurred (Figs. 8 and 9), considering the first and the last years for the evaluated period.

Fig. 8 showed that annual crops in FMA basin have expanded mainly on previous forest and pasture lands. Based on processed satellite images it was possible to confirm that the former forest areas were mainly occupied by annual crops (more than 90% of the replacement). Similarly, about 90% of the decrease in pasture lands was replaced by annual crops. It was also possible to see a slight forest expansion over previous pasture lands (almost 1000 ha). Although the increase over previous forest and pasture lands, sugarcane expansion has occurred mainly over annual crops (almost 60%). Besides, in absolute figures, the advance of annual crops over forest areas (7000 ha) was definitely more significant than for sugarcane (1000 ha).

In MM basin, urban areas expansion covered all the land use classes, advancing over forest (800 ha), pasture (1500 ha), annual and perennial crops (300 ha) and sugarcane (100 ha). Forest grew specially over pasture lands (3000 ha), which in turn expanded over annual and perennial crops (1500 ha). Sugarcane replaced particularly forest and annual crops, even though the expansion

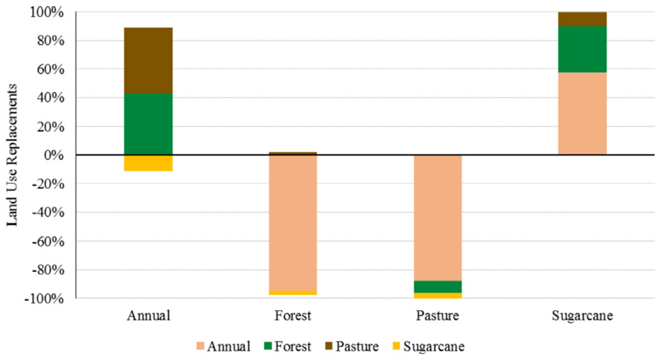


**Fig. 8.** Estimated land use changes in the 2003–2011 period in FMA basin – classes replacement in Brazil.

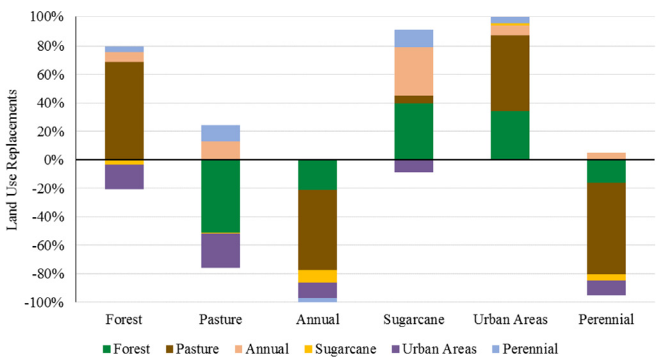


**Fig. 9.** Estimated land use changes in the 1997–2007 period in MM basin – classes replacement in Brazil.

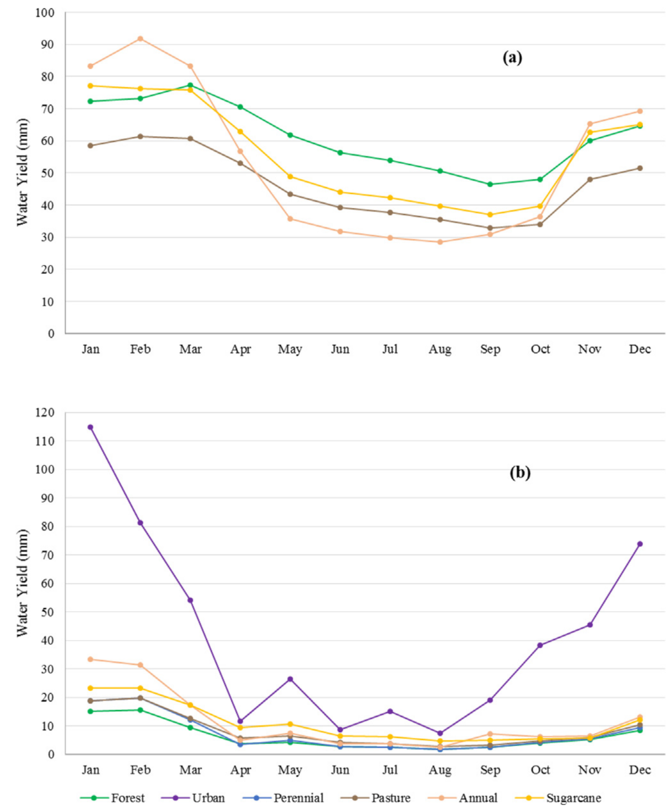


**Fig. 10.** Validated SWAT average water yields for all land uses in FMA (a) and MM (b) basins.

was only 300 ha.

In order to establish a connection between the past land use changes and water resources availability, it was taken from the validated SWAT model, for each land use class, the monthly values of water yield (average for the simulated period), which represents the amount of water that contributes to the basin stream flow (Fig. 10). Furthermore, as an attempt to confirm the assumptions involving land use changes and water yields, and to associate the stream flow response to that, it was plotted, for two years (base map year and the most recent map year), the stream flow behavior versus the accumulated precipitation (Fig. 11).

In terms of water yield for the different land use classes, values in FMA basin appear to be more diverse than those ones in MM basin. In MM case (Fig. 10b), the water yield is driven mainly by the urban areas, with higher values during all the year, especially in wet months. Based on these SWAT results, it is expected in this basin that the more urban areas expand over other land uses, the greater will be the stream flow, particularly in wet months, increasing the flood vulnerability in areas at risk.

In FMA basin (Fig. 10a), water yields for land uses are diverse, either among each other or among the months of the year. Forest water yields were significant and almost continuous during the months, which indicates a more regular stream flow regime in areas covered by this land use class. In wet months, annual crops and sugarcane are the most important contributors to the basin water yield. However, in dry months, annual crops show the smallest water yield values while sugarcane continues to be important in stream flow contributions. Thus, it is possible to affirm that sugarcane water yield in FMA basin performs similarly to forest in dry months. In any case, sugarcane expansion over annual crops tends to increase stream flow in dry periods and decrease peak flows in the basin, making the stream flow regime more regular during the year.

Considering that in FMA basin the major expansion was from annual crops over forest and pasture lands, according to the water yield results, stream flow would be expected to rise in wet months and to decline in dry months. On the other hand, a significant sugarcane increase might mitigate these effects, making the changes in stream flow less significant. In MM basin, changes were less important in terms of absolute values. There was an increase in urban areas, which according to the water yield should cause an increase in stream flow values, mostly in wet months. However, an observed growth of forest at the same magnitude in the evaluated period is expected to attenuate the changes in stream flow.

The stream flow for the FMA basin (Fig. 11a), comparing 2011 to 2003, indicates an increase in monthly average stream flow values, particularly in dry months, even with the smaller accumulated precipitation in 2011 compared to 2003. These results partially confirm the basin land use change assumptions from water yields assessment. On the other hand, a higher stream flow value in January 2011 versus January 2003 may have been somehow responsible for the results in the subsequent dry months. Values in January 2011 was certainly influenced by the high accumulated precipitation from the previous months (November and December of 2010), which achieved 554 mm. The accumulated precipitation for November and December of 2002 was only 283 mm.

In the MM basin (Fig. 11b), stream flow values in relation to the precipitation were almost the same, which was also in accordance to the expected effects from land use change and water yields. In this case, there were no inconsistencies involving precipitation amounts and stream flow responses as in FMA basin. Nevertheless, a peak in accumulated precipitation from June 1997 to July 1997 (22% of increase in precipitation) caused a high stream flow value in

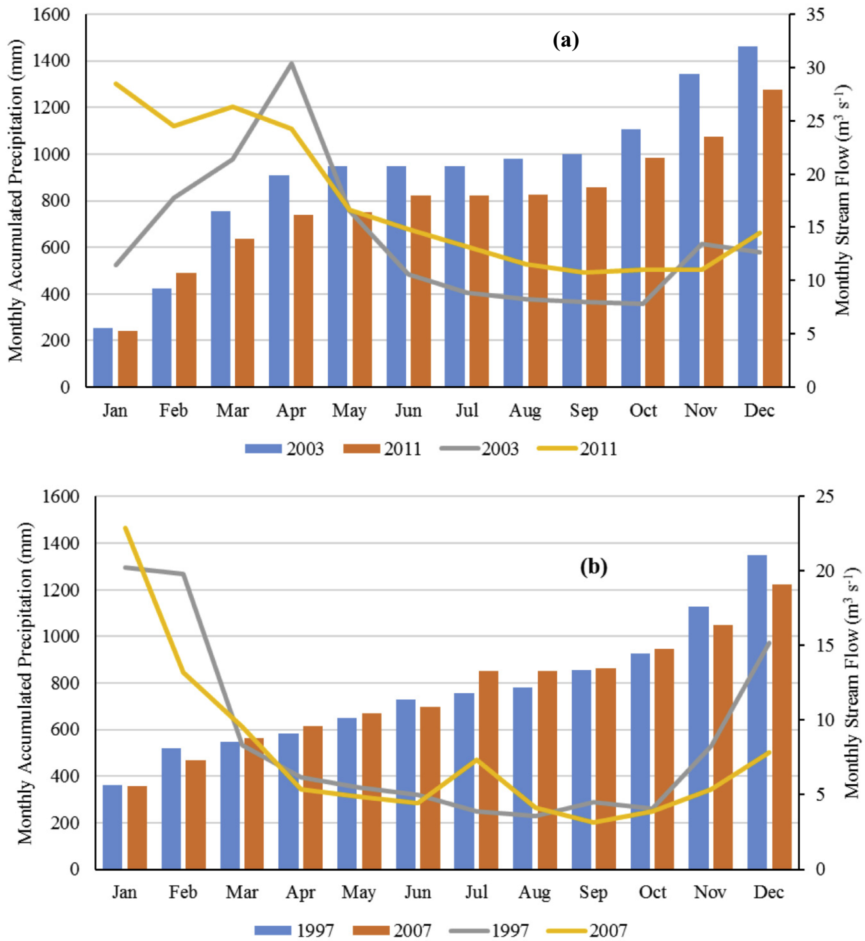


**Fig. 11.** Accumulated precipitation (bars) versus average stream flow values (lines) in FMA (a) and MM (b) basins.

this last month (108%), which evidences the high response of the basin to precipitation events, as previously supposed due to the high level of urbanization. Similar behavior can be observed from October 2007 to December 2007, during which an increase of 46% in precipitation induced a stream flow growth of 400%.

Even though the main assumptions of land use change impacts on stream flow have been confirmed, the high dependence of the precipitation amounts (Guarenghi and Walter, 2016) and also the influence of other parameters as the precipitation amounts from the previous months, make it very difficult to quantify the land use change effects on stream flow from the other possible interferences. Nevertheless, the integrated assessment of the SWAT water balance components (precipitation, water yields and stream flow) enabled a more comprehensive analysis of the land use change effects on water availability.

## 4. Conclusions

Successful SWAT calibration and validation were achieved for the assessed basins, highlighting the great potential use of the model in the planning and management of the water resources. On the other hand, as SWAT is an input intensive model, difficulties are expected in input data collection in Brazil, especially regarding soil information. In addition to ensuring a more reliable calibration and validation process, the careful model setup concerning the local crop and management related parameters, as well as the previous evaluation of the stream flow performance for the different runoff methods and the land use changes update over the simulation period, enabled the achievement of consistent results regarding crop evapotranspiration and crop yields in the assessed basins.

During the considered period of evaluation, the assessed basins presented diverse land use change dynamics. In FMA basin, annual crops and sugarcane expanded, while forest and pasture lands reduced. In MM basin, forest and urban areas increased and the remaining land uses stagnated or were reduced.

In general, water yield results indicate that sugarcane expansion over annual crops tends to increase stream flow in dry periods and decrease peak flows, making the water regime more regular during the year. They also indicate that urban areas expansion increases the stream flow in wet months, hence contributing to flood vulnerability in areas at risk. Therefore, sugarcane expansion can be monitored and oriented, by means of public policies and other government measures, towards pasture and annual crop areas in order to maintain the positive impacts on water availability.

Despite the difficulties to separate the land use change effects from other stream flow impacting parameters, such as the previous accumulated precipitation, the integrated assessment of stream flow, water yields and precipitation from SWAT model give reasonable qualitative responses in the assessment of the land use change impacts on water resources availability.

For past evaluations, the use of SWAT in a basin with more intense sugarcane expansion should allow more consistent

quantification of sugarcane impacts on water resources availability. However, the model has a promising application in the basins planning and management, after successful calibration and validation; possible future land use scenarios or even climate changes could be assessed. Therefore, the quantification of the exclusive sugarcane impacts can be made with the simulation of scenarios considering larger increases in sugarcane areas replacing specific land use classes and stationary conditions for the remaining land uses and water balance components.

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